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Probing New Physics with Double Beta Decay

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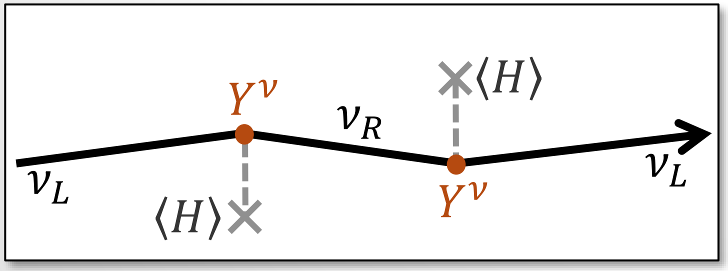
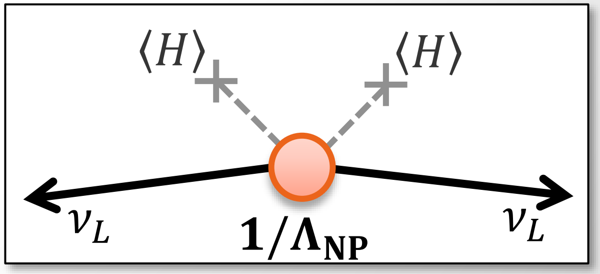
Dirac versus Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

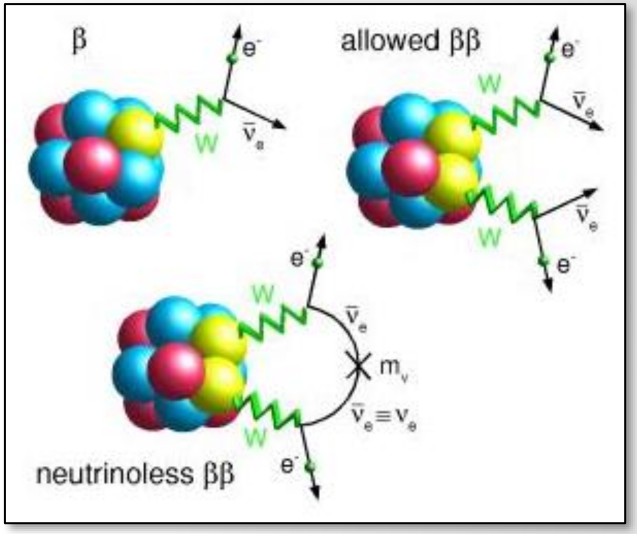
Majorana mass, using only a left-handed neutrino → Lepton Number Violation

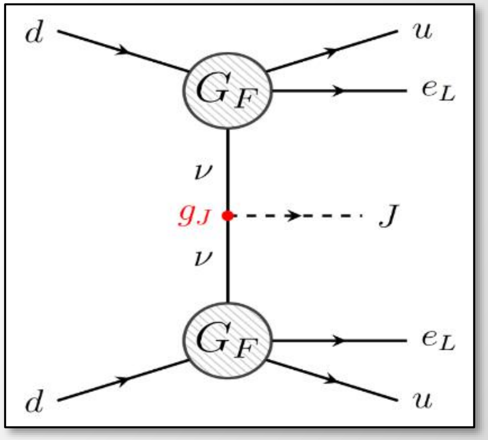




Beta Decays and ν Nature

- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Tritium decay, KATRIN: $\boldsymbol{m_\beta \approx 0.2}$ **eV**
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $\boldsymbol{m_\beta \approx 0.05}$ **eV**
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos
- Majoron assisted double beta ($0\nu\beta\beta J$) decay
  - Missing energy → lepton number violated?





Neutrinoless Double β Decay

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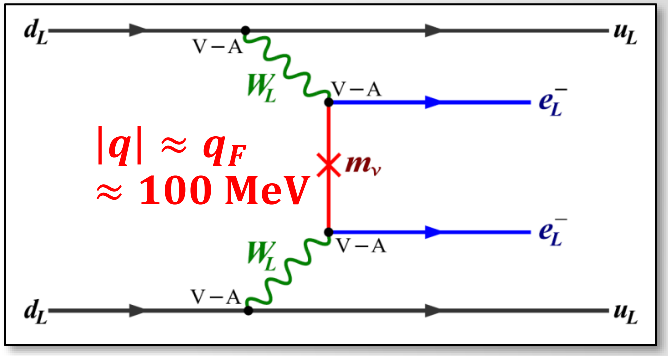
- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$

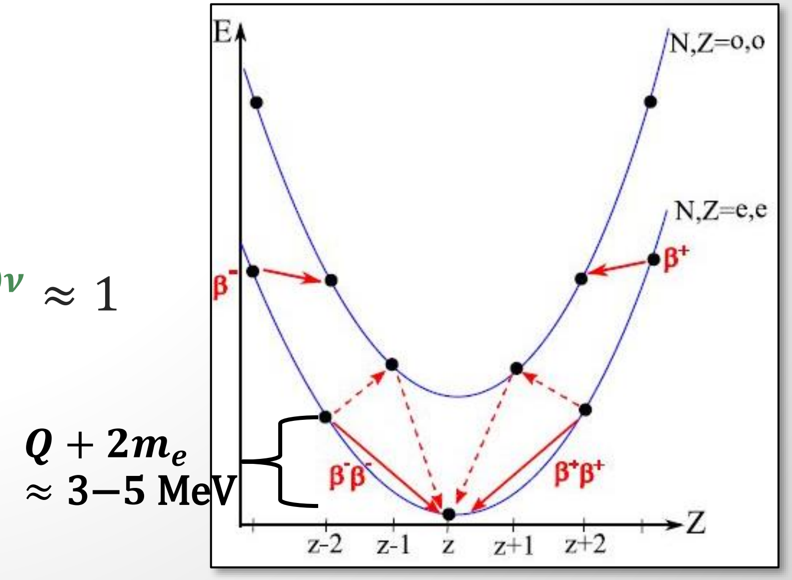


- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu(1+\gamma_5)\frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

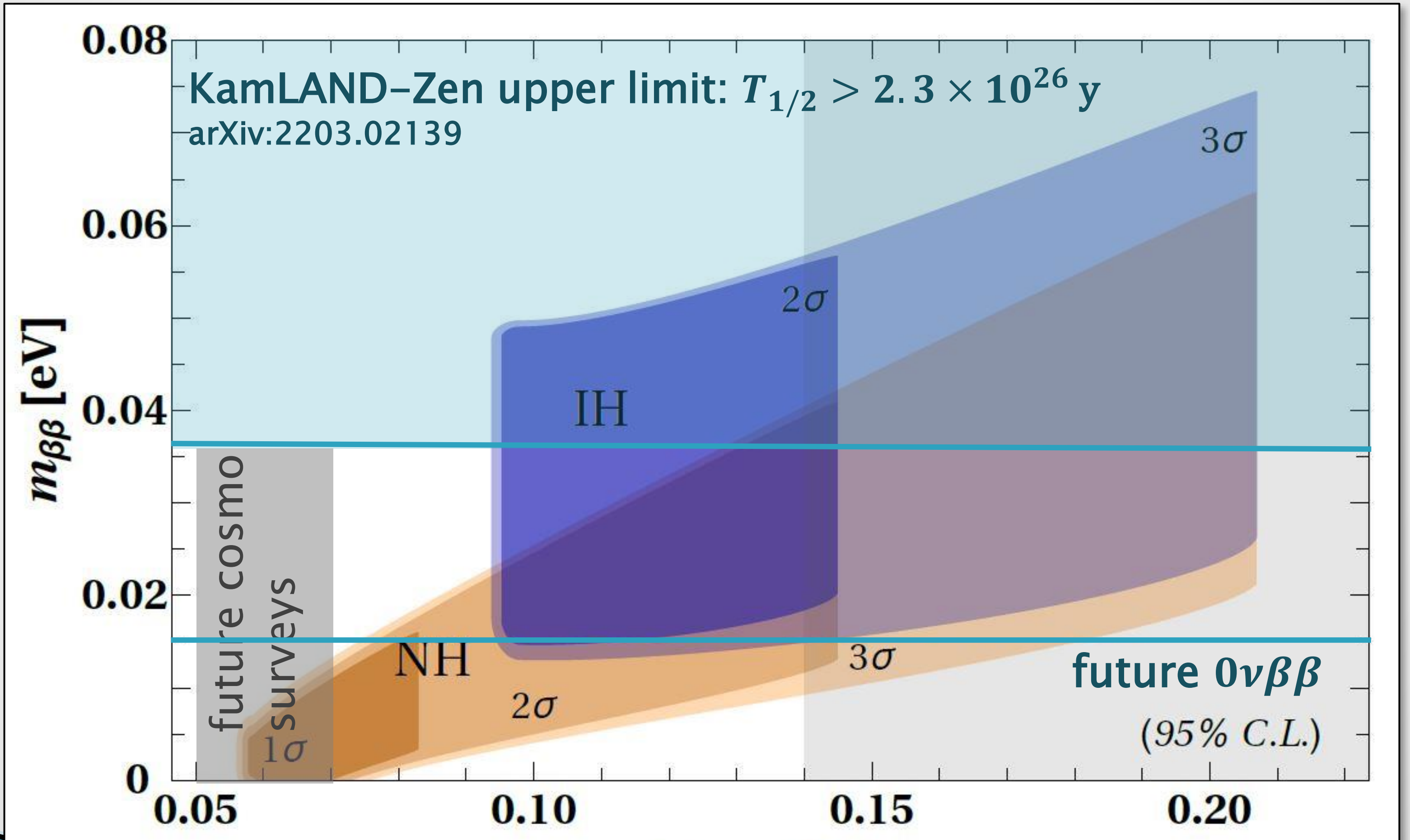
- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$ but large uncertainties, factor 2–3

$$\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$



Three Active Neutrinos

- Effective $0\nu\beta\beta$ Mass



Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

New Physics and $0\nu\beta\beta$

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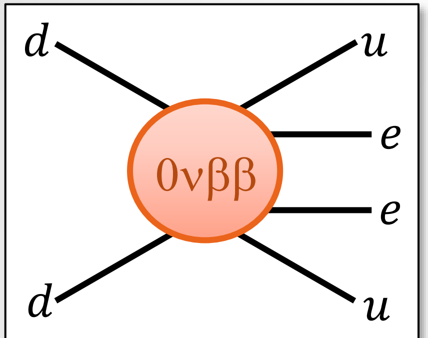
- Plethora of New Physics scenarios



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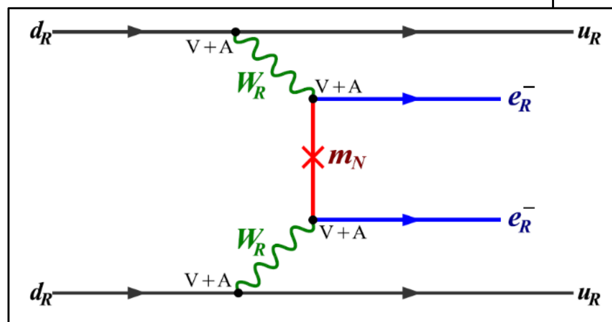
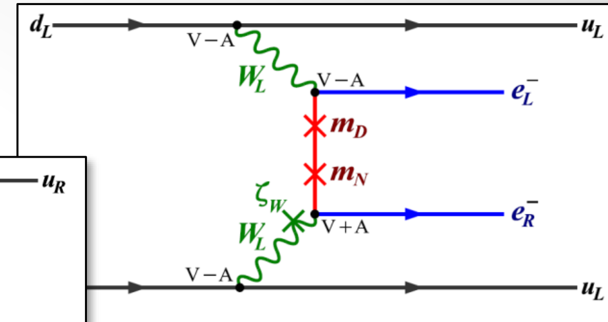
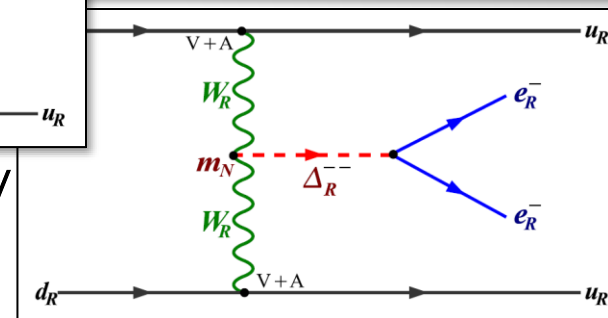
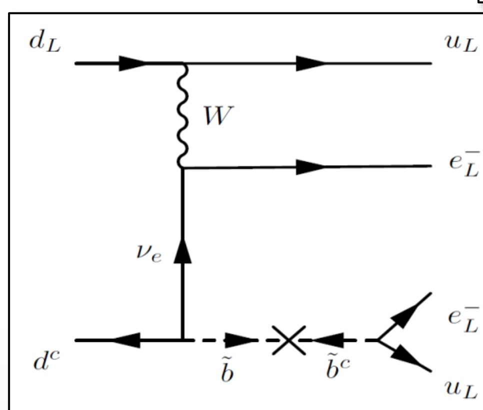
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

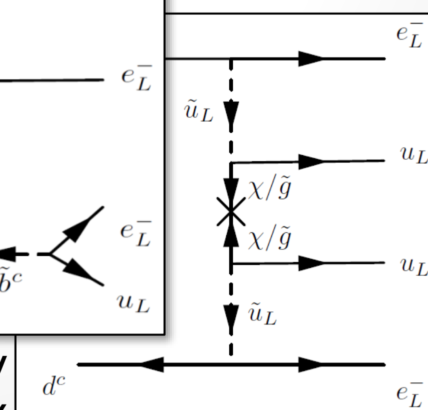






Left-Right Symmetry



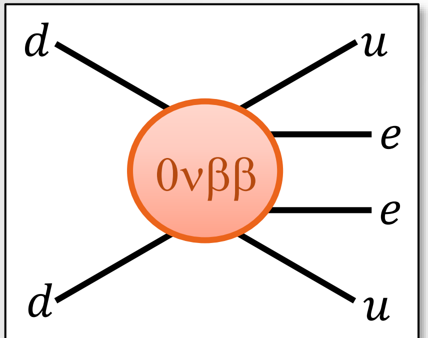


R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- …

New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios



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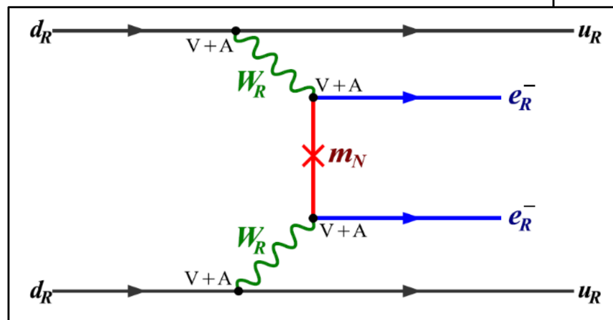
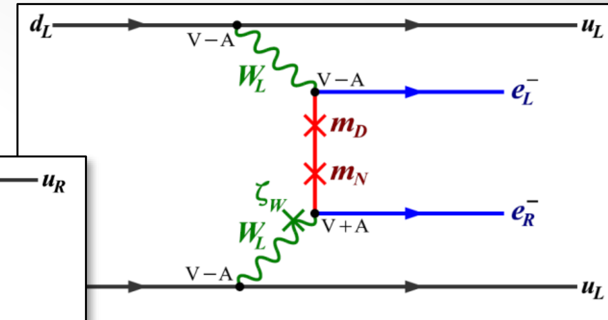
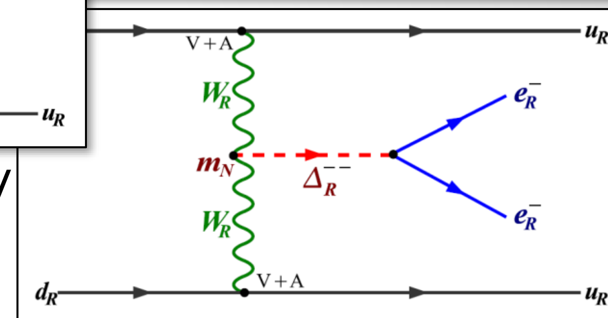




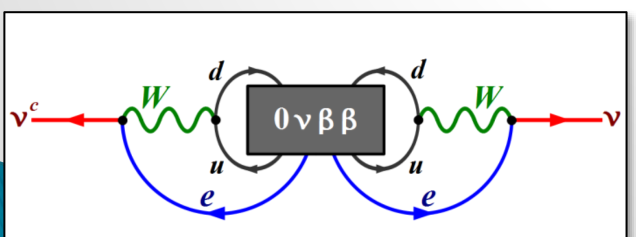


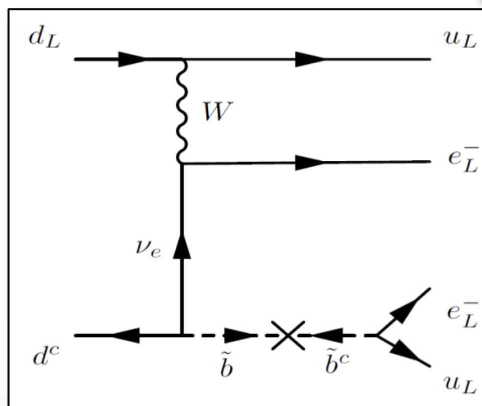
Left-Right Symmetry

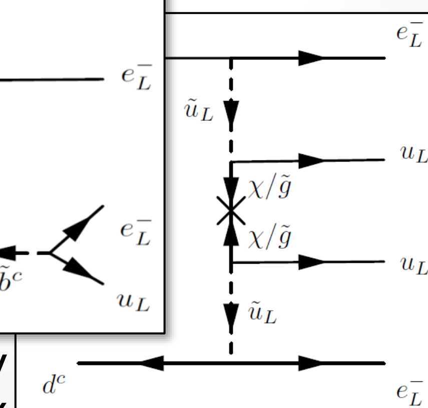
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

- Neutrinos still Majorana

Schechter, Valle, Phys.Rev.D 25 (1982) 2951





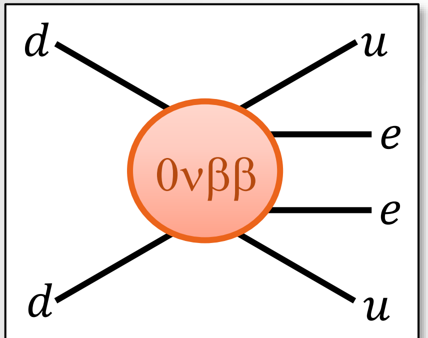


R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- …

New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry



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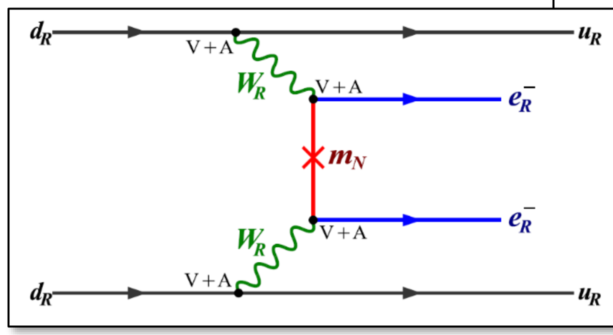
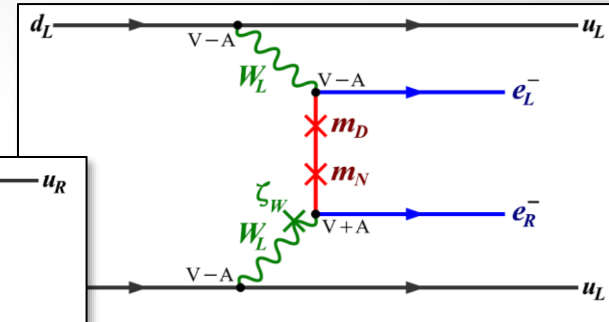


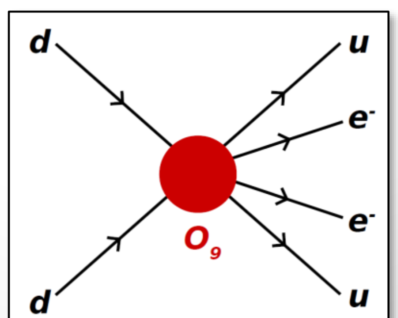


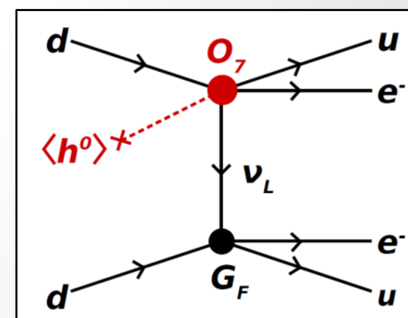
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators





Short-Range Mechanisms

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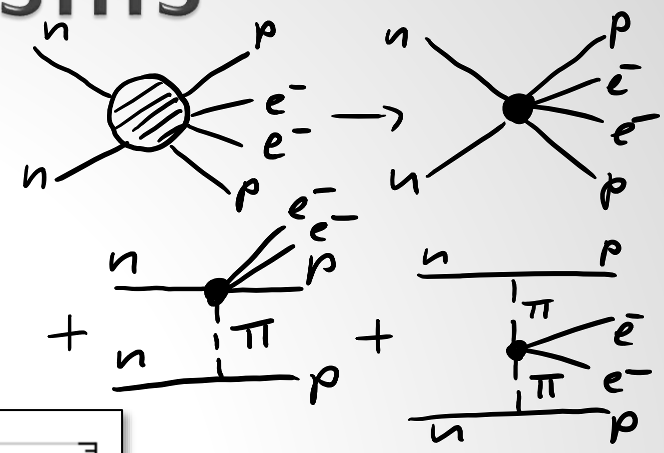
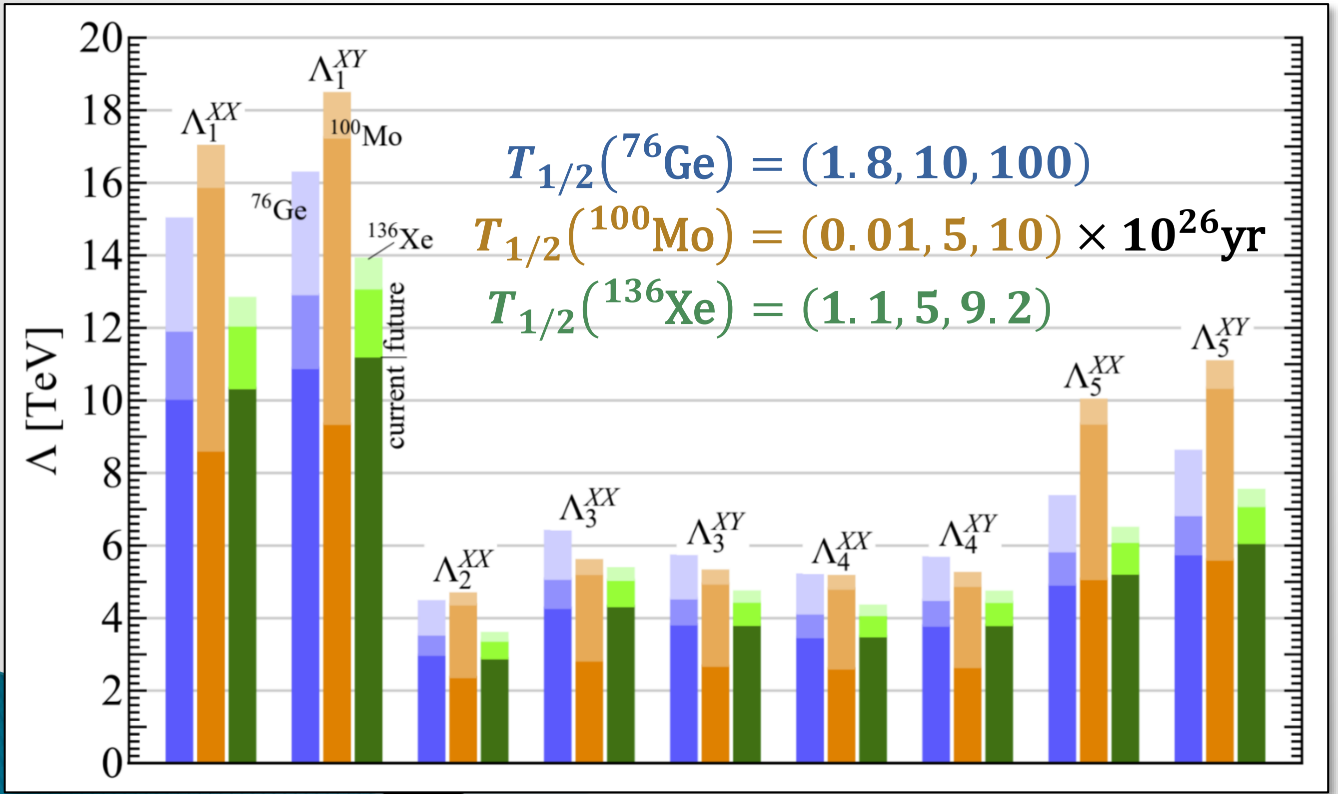
FFD, Graf, Iachello, Kotila, PRD 102 (2020)

- Limits on short-range operators
  - NMEs from IBM-2 with $g_A = 1.0$ and short-range correlations in Argonne parametrization





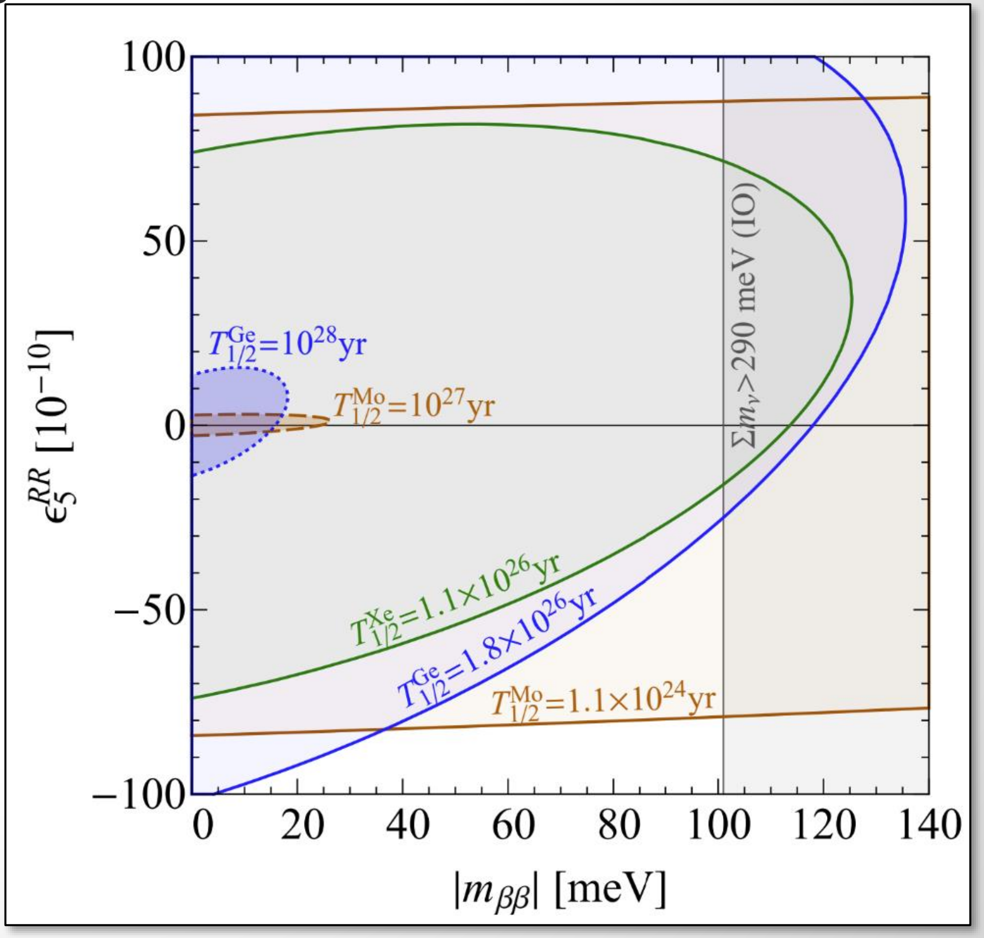
Pion-mediated contributions

- R-parity violating SUSY (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
- Chiral EFT with Pion operators from Lattice QCD (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)

Short-Range Mechanisms

FFD, Graf, Iachello, Kotila, PRD 102 (2020)

- Limits on short-range operators
  - NMEs from IBM-2 with $g_A = 1.0$ and short-range correlations in Argonne parametrization
- Interference with standard massmechanism



Disentangling New Physics

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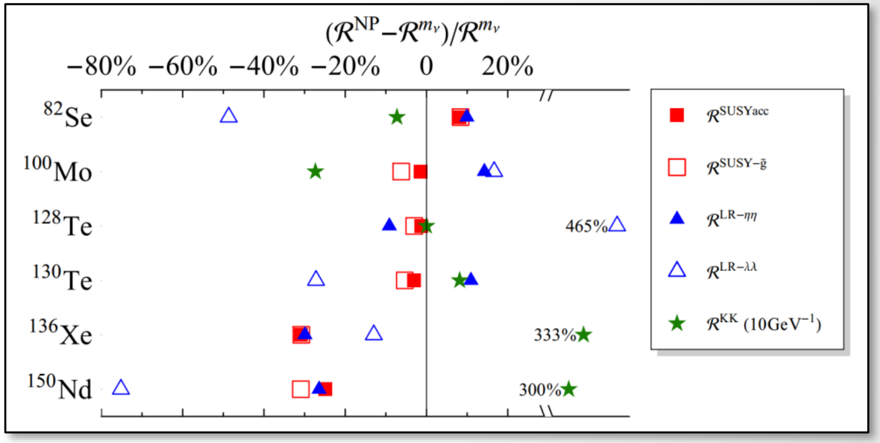
- Comparison of $0\nu\beta\beta$ in multiple isotopes
  FFD, Päs, Phys.Rev.Lett. 98 (2007) 232501
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics (if one mechanism dominates)

$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



- Angular and energy distribution of emitted electrons
  Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10

$$\frac{d\Gamma}{dE_{e_1}dE_{e_2}d\cos\theta} = \frac{\Gamma}{2}\left(1 - k(E_{e_1},E_{e_2})\cos\theta\right), \qquad -1 < k < 1$$

  - Linear in $\cos\theta$
  - $k(E_{e_1},E_{e_2})$ depends on $0\nu\beta\beta$ mechanism

Disentangling New Physics

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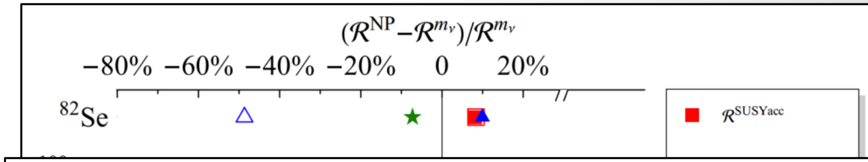
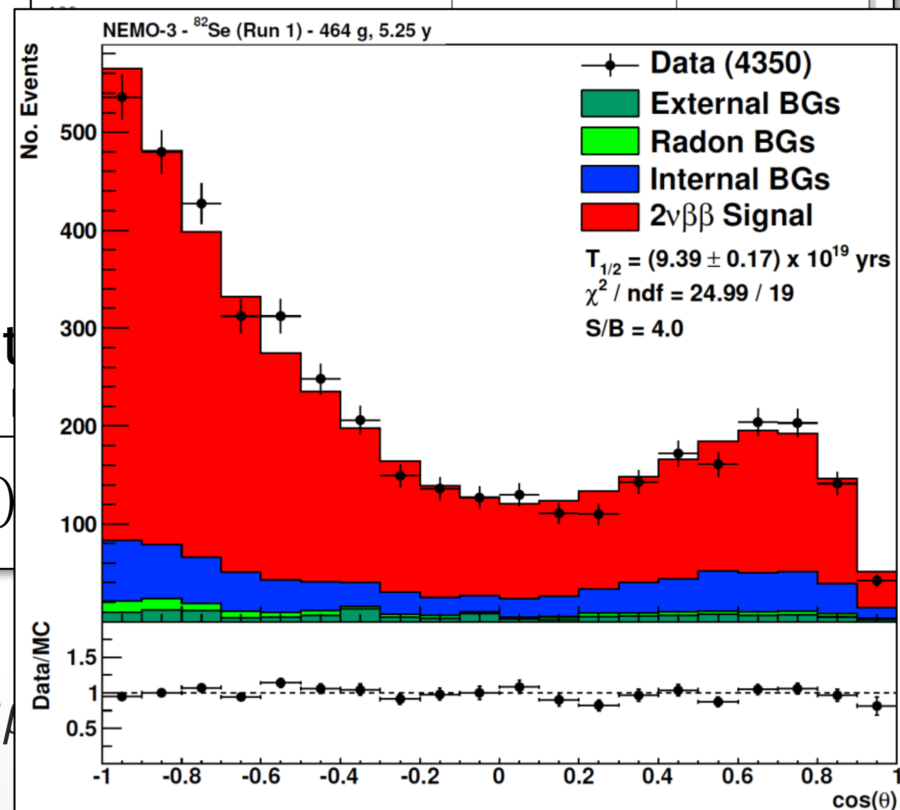


- Angular and energy distribut
  Doi et al. '83; Ali et al. '06; Arnold et al. '10;

$$\frac{d\Gamma}{dE_{e_1} dE_{e_2} d\cos\theta} = \frac{\Gamma}{2}\left(1 - k(E_{e_1}, E_{e_2})\cos\theta\right)$$

  - Linear in $\cos\theta$
  - $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta$

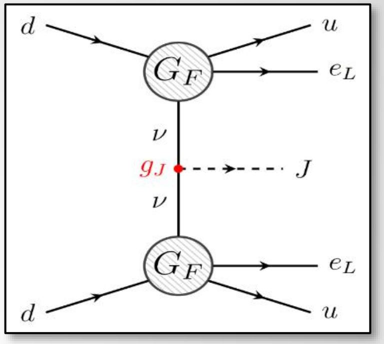


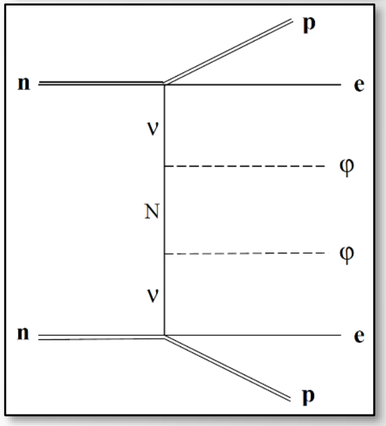
Majorons and MLPs

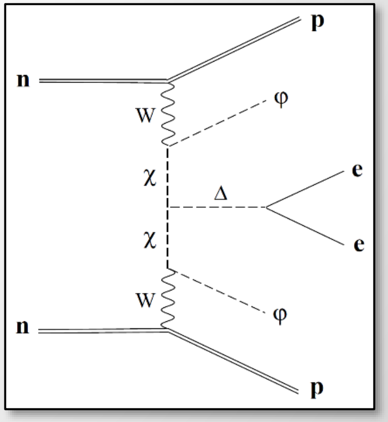
- Emission of one or more neutral bosons
  - Majoron model of neutrino mass generation
  - "Majoron-like" boson J with coupling to ν, e.g. $g_{ij}\bar{\nu}_i\gamma_5\nu_j J$
  - Light scalar associated with Weinberg-like operator (Blum, Nir, Shavit, Phys. Lett. B785 (2018) 354)

$$\mathcal{L}_{d=6} = -\frac{\mathcal{Y}_{\alpha\beta}}{\Lambda^2}\phi(HL_\alpha)(HL_\beta)$$

  - Extensions with derivative couplings or two-Majoron emission





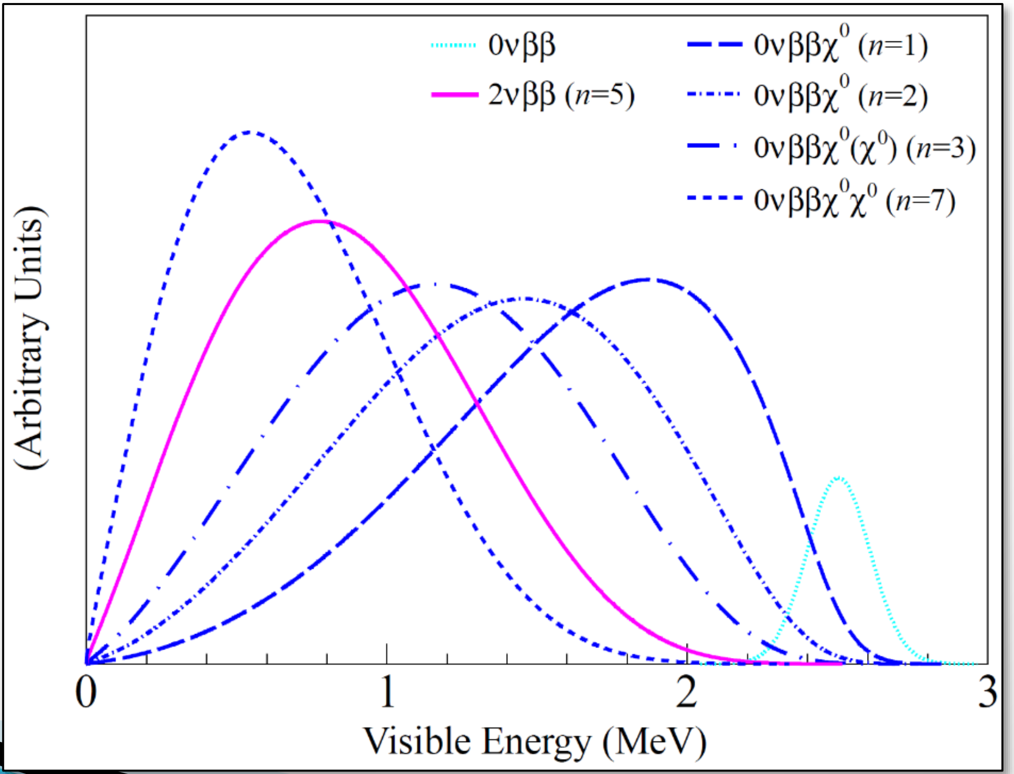


Bamert, Burgess, Mohapatra '95

Majorons and MLPs

- Standard Majoron classes
  - Electron energy distribution

$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \ [p_1\varepsilon_1 F(\varepsilon_1)] \ [p_2\varepsilon_2 F(\varepsilon_2)]$$



Majorons and MLPs

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- Standard Majoron classes

Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ $[10^{23}\text{yr}]$	$\mathcal{M}^{0\nu\chi}$	$G^{0\nu\chi}$ $[\text{yr}^{-1}]$	$\langle g \rangle$
IB	1	χ	no	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IC	1	χ	yes	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
ID	3	$\chi\chi$	no	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	yes	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IF	2	χ	bulk field	0	> 1.8	–	–	–
IIB	1	χ	no	-2	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IIC	3	χ	yes	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$
IID	3	$\chi\chi$	no	-1	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	yes	-1	> 0.3	$10^{-3\pm1}$	$1.21 \cdot 10^{-18}$	$< 2.2^{+4.9}_{-1.4}$
IIF	3	χ	gauge boson	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$

GERDA, Eur. Phys. J. C75 (2015) 9, 416

Majorons and RH Currents

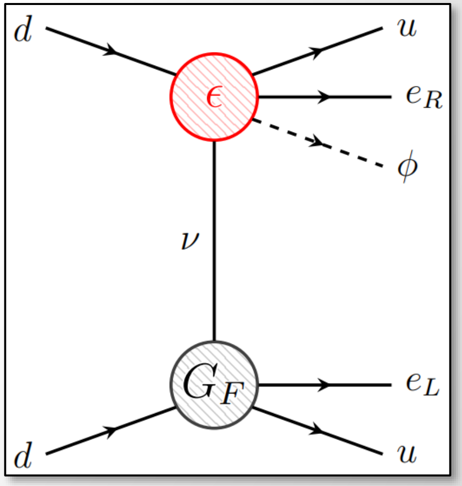
Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Effective RH lepton currents with massless scalar ϕ

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}}\left(j_L^\mu J_{L\mu} + \frac{\epsilon^\phi_{RL}}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon^\phi_{RR}}{m_p} j_R^\mu J_{R\mu}\phi\right) + \text{h.c.}$$

- Giving rise to long-range contribution to $0\nu\beta\beta\phi$ decay

$$\mathcal{M} = \epsilon^\phi_{RX}\frac{(G_F\cos\theta_C)^2}{\sqrt{2}m_p}\sum_N \int d^3x d^3y \int \frac{d^3q}{2\pi^2\omega}\phi(\mathbf{y})e^{i\mathbf{q}(\mathbf{x}-\mathbf{y})}$$
$$\times\left\{\left[\frac{J^{\rho\sigma}_{LX}(\mathbf{x},\mathbf{y})u^L_{\rho\sigma}(E_1\mathbf{x},E_2\mathbf{y})}{\omega+\mu_N-\frac{1}{2}(E_1-E_2-E_\phi)} - \frac{J^{\rho\sigma}_{XL}(\mathbf{x},\mathbf{y})u^R_{\rho\sigma}(E_1\mathbf{x},E_2\mathbf{y})}{\omega+\mu_N-\frac{1}{2}(E_1-E_2+E_\phi)}\right] - \left[E_1 \leftrightarrow E_2\right]\right\}$$



  - No suppression with ν mass

- Calculation follows long-range η and λ $0\nu\beta\beta$ modes
Doi, Kotani, Takasugi, Prog. Theor. Phys. Suppl. 83 (1985) 1

Majorons and RH Currents

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

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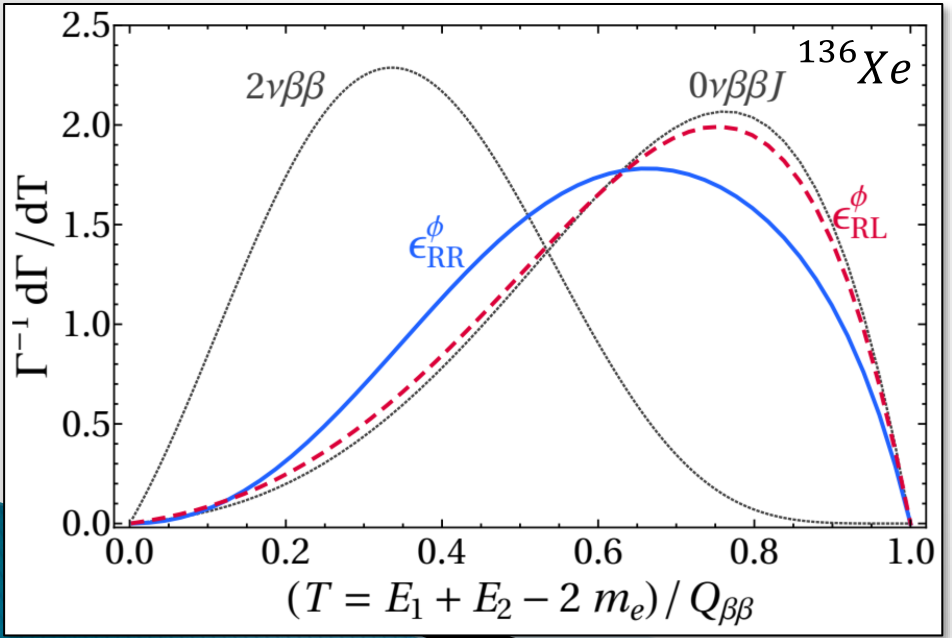
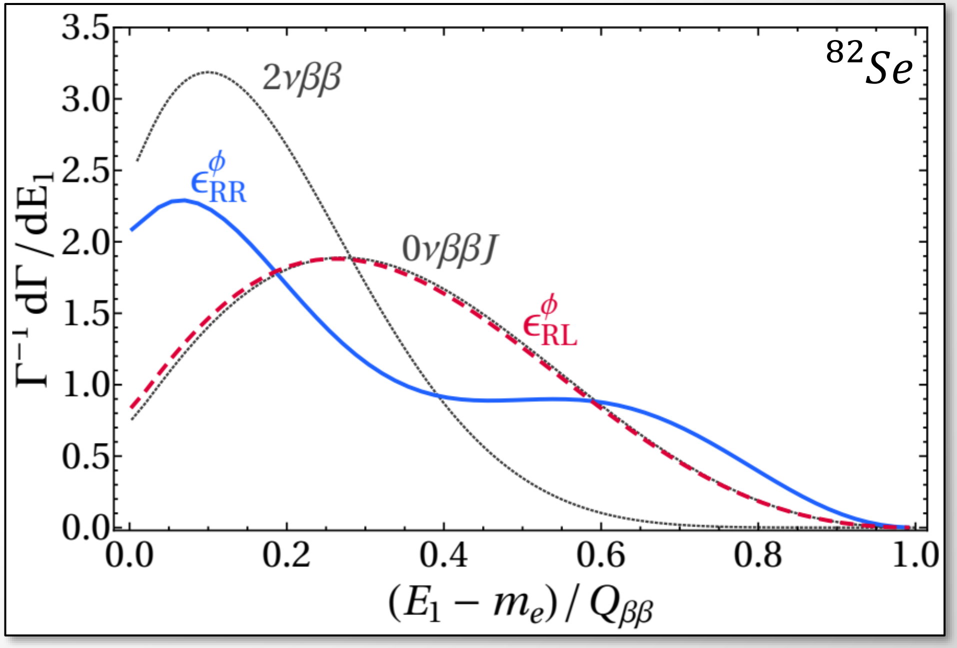
$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$

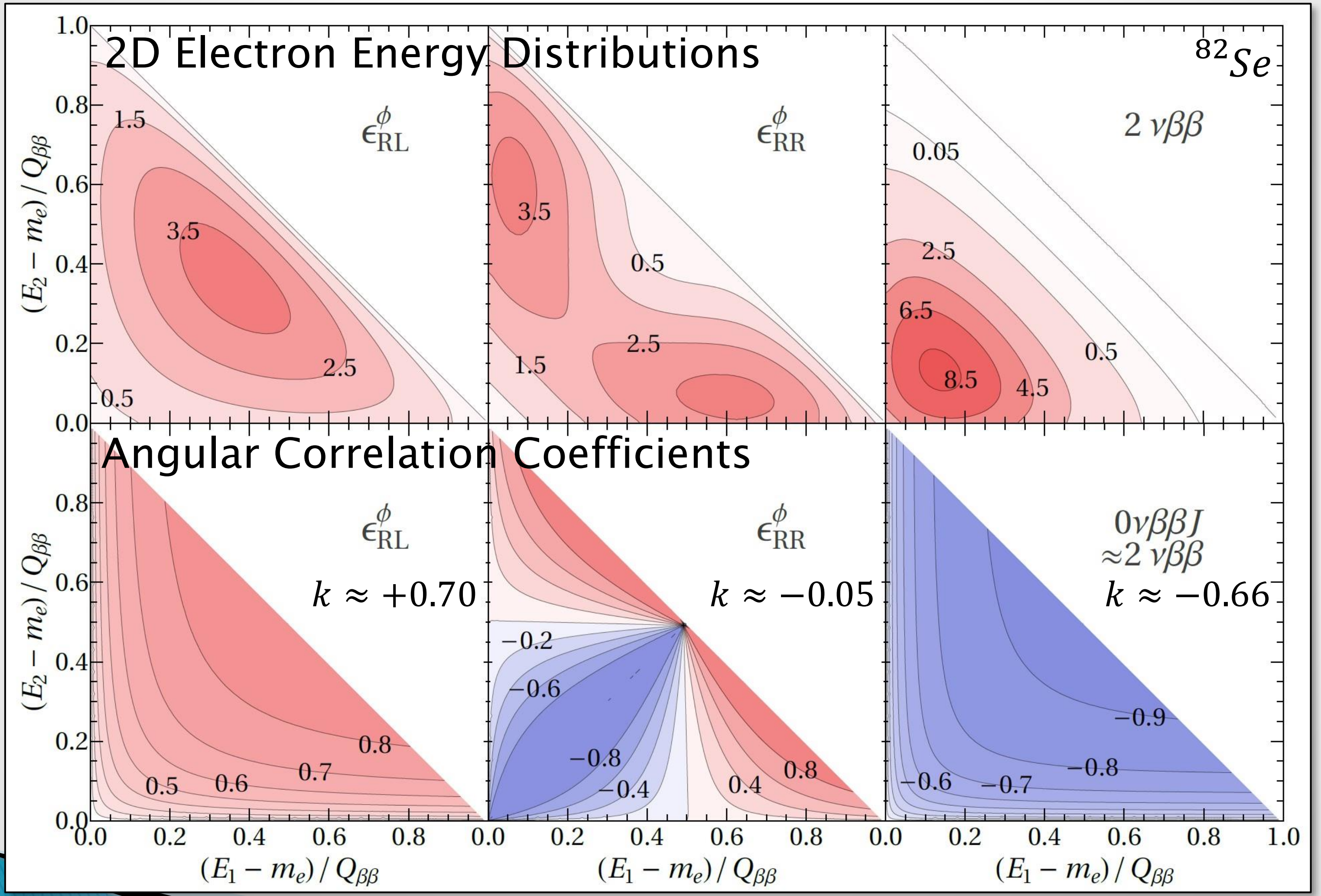
- Non-standard total and single electron energy distributions





Majorons and RH Currents

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801



Majorons and RH Currents

UCL University College London

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Sensitivity (massless ϕ, recasting single Majoron searches)

Isotope	$T_{1/2}$ [y]	$\lvert\epsilon^{\phi}_{RL}\rvert$	$\lvert\epsilon^{\phi}_{RR}\rvert$
^{82}Se	3.7×10^{22} [14]	4.1×10^{-4}	4.6×10^{-2}
^{136}Xe	2.6×10^{24} [13]	1.1×10^{-4}	1.1×10^{-2}
^{82}Se	1.0×10^{24}	8.0×10^{-5}	8.8×10^{-3}
^{136}Xe	1.0×10^{25}	5.7×10^{-5}	5.8×10^{-3}

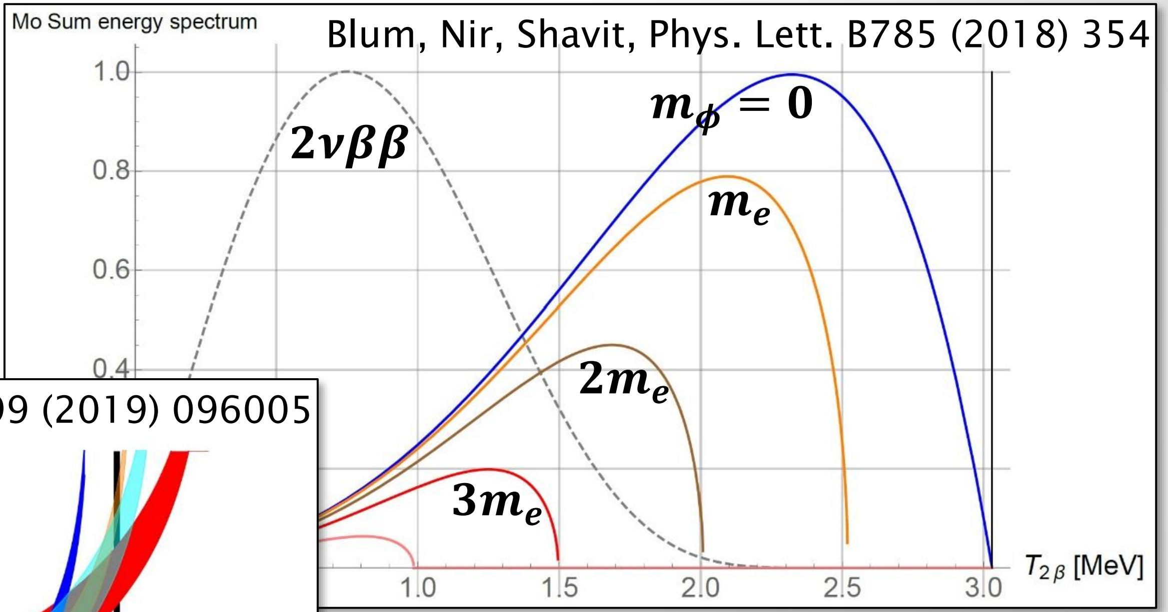
- Searched for in EXO-200
  (PRD 104 (2021) 11, 112002)

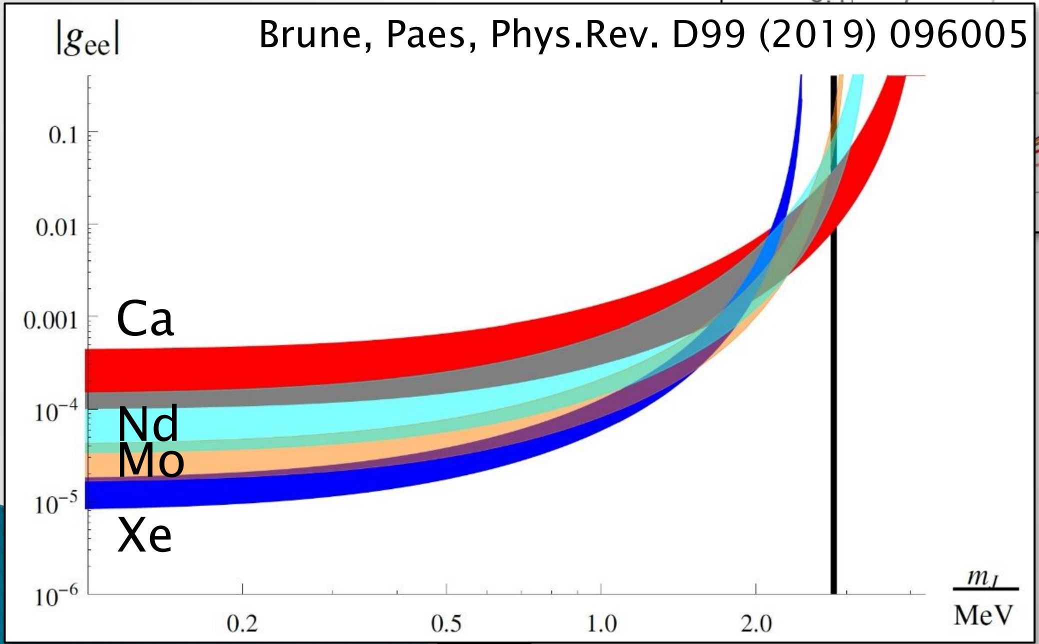
$$T_{1/2}^{Xe} > 4 \times 10^{24}\ \mathrm{y}$$

Majorons and RH Currents

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Sensitivity modification for massive ϕ
  - Suppression of phase space
  - Decrease of $S/\sqrt{B}$





UV Model: LR Symmetry

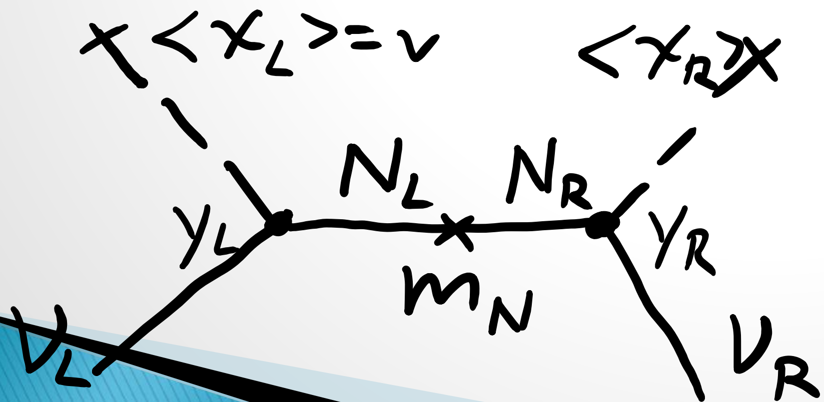
Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Extended Gauge Symmetry

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Minimal LR model: $X = B - L$
- We consider $X \neq B - L$ broken but $B - L$ conserved
- Dirac neutrinos (and charged SM fermions) via Dirac seesaw via heavy, vector-like fermions (Bolton, FFD, Hati, arXiv:1902.05802)

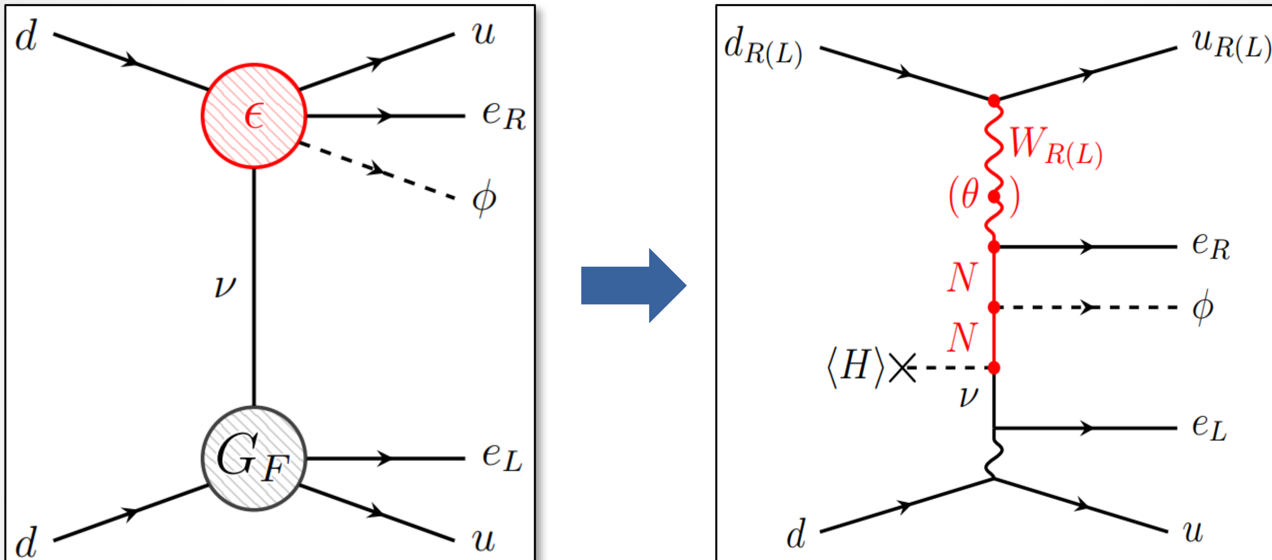
Field	$SU(2)_L$	$SU(2)_R$	$B-L$	ζ	X	$SU(3)_C$
q_L	2	1	1/3	0	1/3	3
q_R	1	2	1/3	0	1/3	3
ℓ_L	2	1	-1	0	-1	1
ℓ_R	1	2	-1	0	-1	1
$U_{L,R}$	1	1	1/3	+1	4/3	3
$D_{L,R}$	1	1	1/3	-1	-2/3	3
$E_{L,R}$	1	1	-1	-1	-2	1
$N_{L,R}$	1	1	-1	+1	0	1
χ_L	2	1	0	+1	1	1
χ_R	1	2	0	+1	1	1
ϕ	1	1	2	-2	0	1



UV Model: LR Symmetry

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- UV Diagram



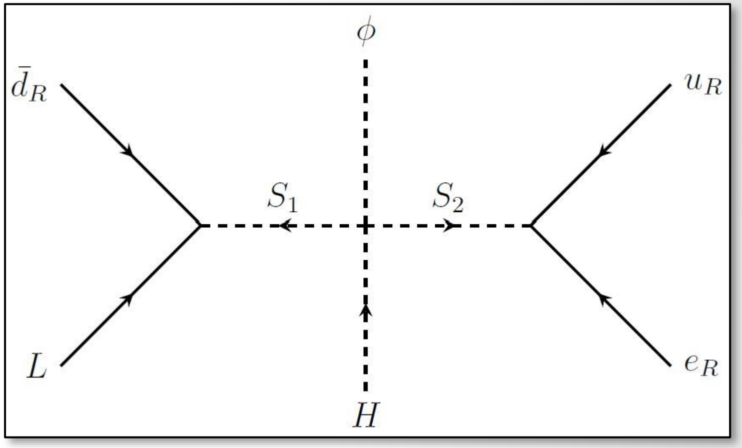
- Sensitivity from ϵ_{RL}^{ϕ}

$$\frac{T_{1/2}^{\mathrm{Xe}}}{10^{25}\ \mathrm{y}} \approx \left(\frac{1.4\times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \mathrm{TeV}}\right)^4 \left(\frac{m_N}{100\ \mathrm{MeV}}\right)^4$$

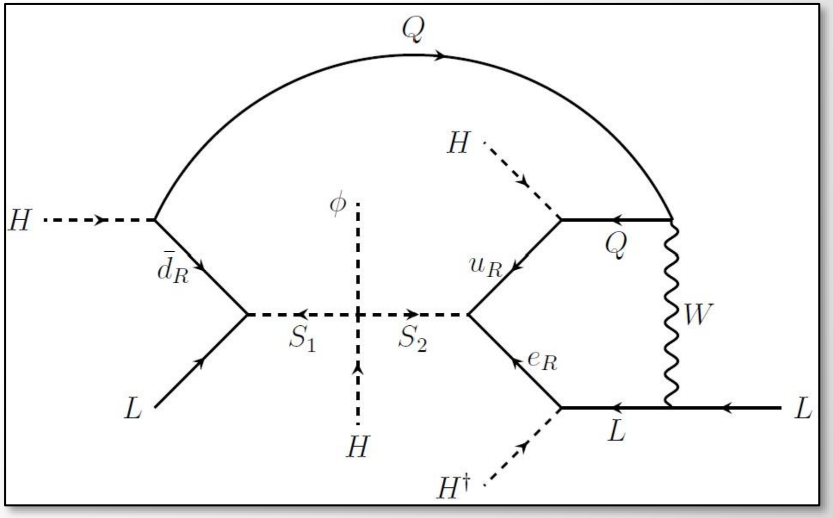
UV Model: Leptoquarks

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Add heavy scalar leptoquarks $S_1(3,2,1/6)$, $S_2(3^*,1,1/3)$
  - Effective operator at tree level
  - Lepton number conserved if $L(S_1) = L(S_2) = -1$, $L(\phi) = -2$



  - LNV and Majorana neutrino mass at two-loop if $\langle\phi\rangle \neq 0$

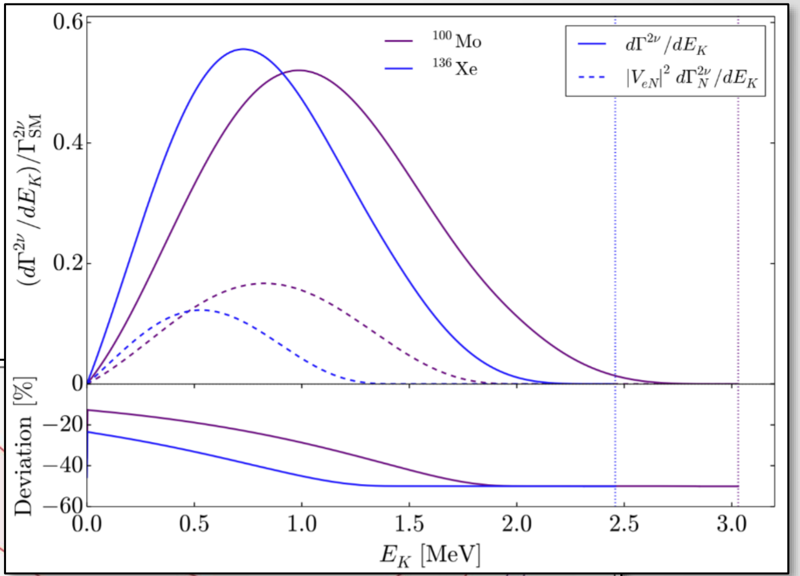


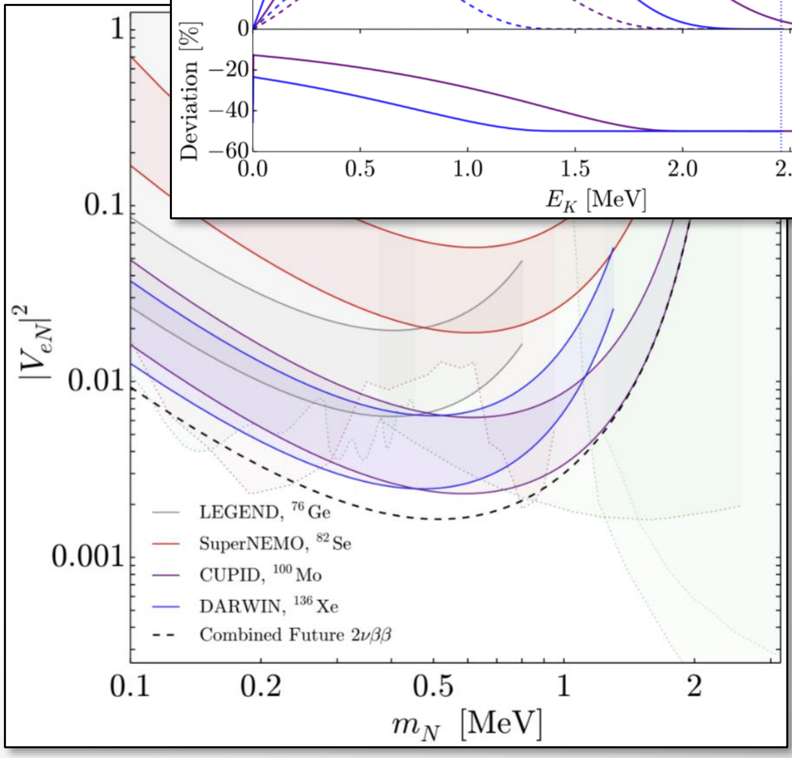
New Physics in $2\nu\beta\beta$

Bolton, FFD, Graf, Simkovic, Phys.Rev.D 103 (2021) 055019

- Sterile neutrino search through energy endpoint (also Agostini, Bossio, Ibarra, Marcano, PLB 815 (2021))
  - Emission of one sterile neutrino in double beta decay: $\nu N\beta\beta$
  - Same principle as endpoint searches in single β decays
  - Observed limit at GERDA (JCAP 12 (2022) 012)

$$|V_{eN}|^2 < 1.3 \times 10^{-2}$$

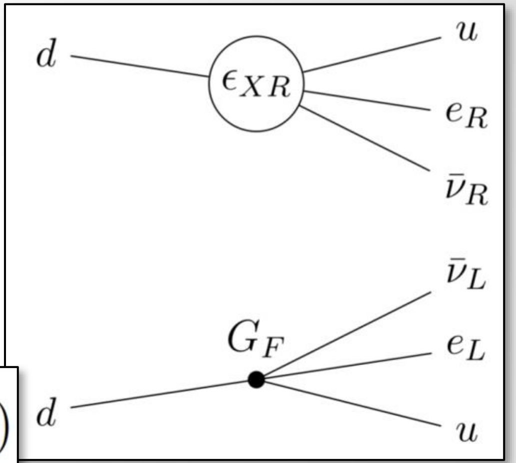




New Physics in $2\nu\beta\beta$

FFD, Graf, Simkovic, Phys.Rev.Lett. 125 (2020) 17, 171801

- Lepton number conserving RH currents
  - Exotic charged currents probed e.g.
    - in neutron and single β decay
    - at LHC in $pp \to eX + MET$
  - Limits on RH currents



$$\frac{G_F \cos\theta_C}{\sqrt{2}}\left((1+\delta_{\mathrm{SM}}+\epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu}\right)$$

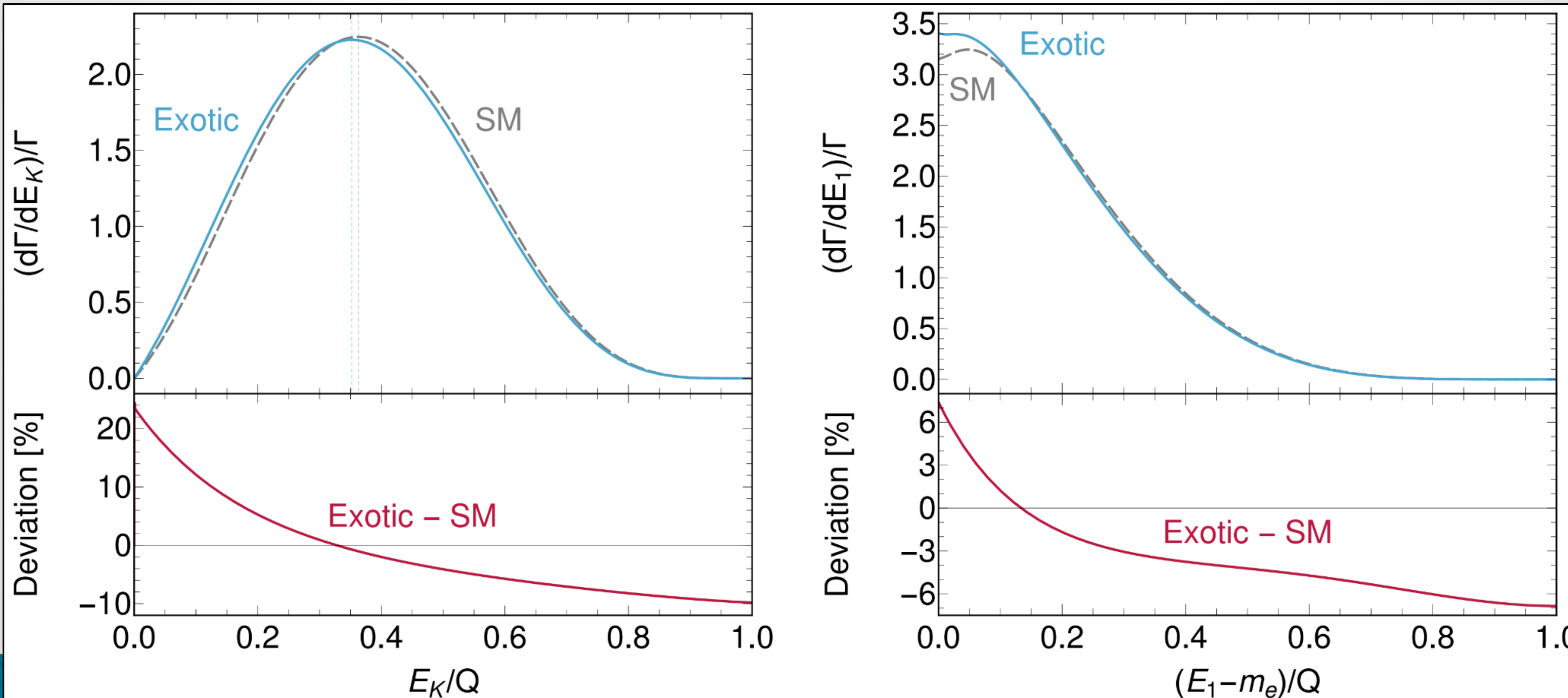
less severe due to lack of interference with SM

- Modification of angular and energy distribution in $2\nu\beta\beta$ decay
  - Observation of two e^- instead of one in single β decay
  - Current limit $\epsilon_{XR} < 3 \times 10^{-2}$ from NEMO3 competitive to other searches

New Physics in $2\nu\beta\beta$

FFD, Graf, Simkovic, Phys.Rev.Lett. 125 (2020) 17, 171801

- Lepton number conserving RH currents
  - Main effect: Opposite angular distribution
  - Small modification of energy distribution



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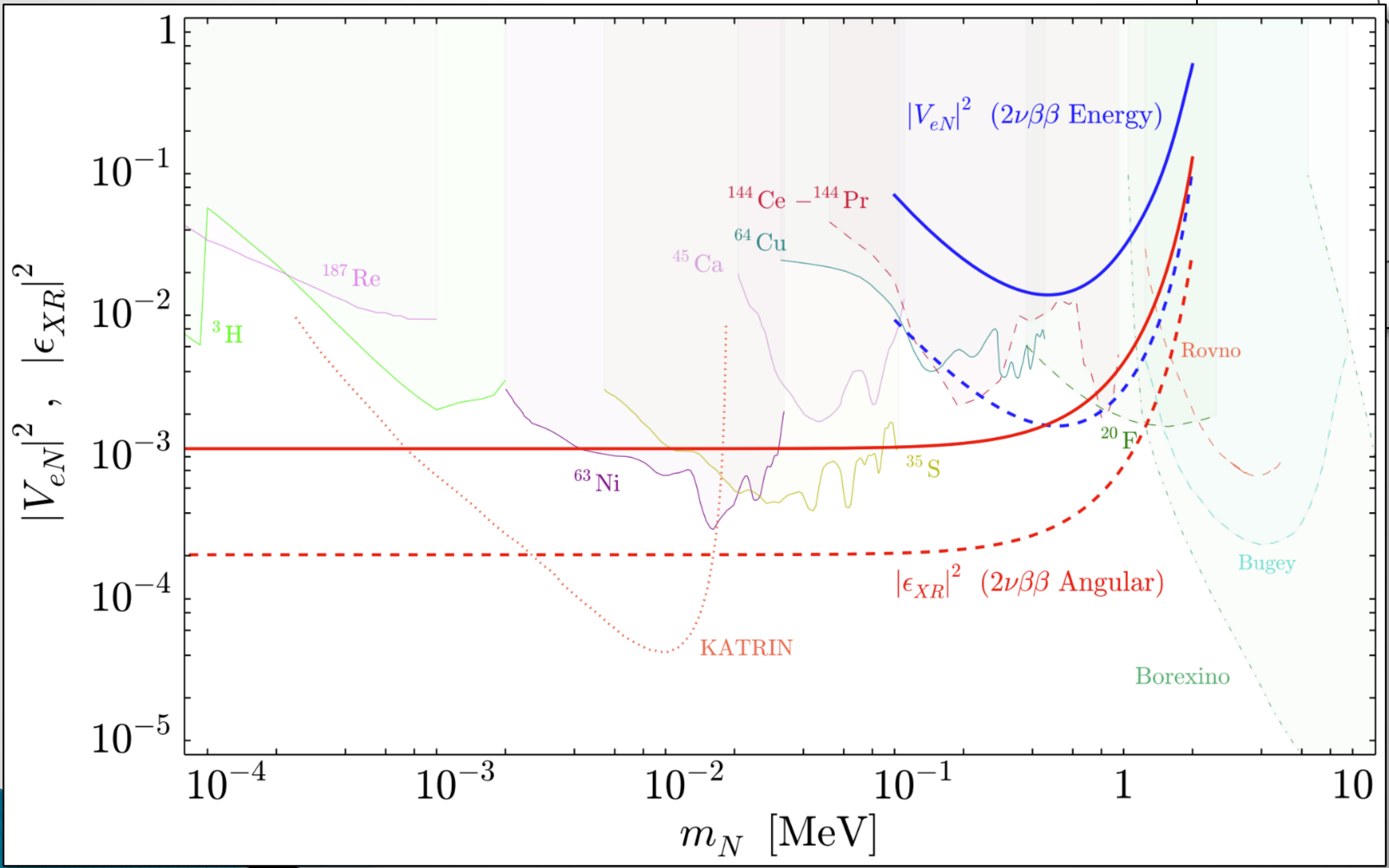
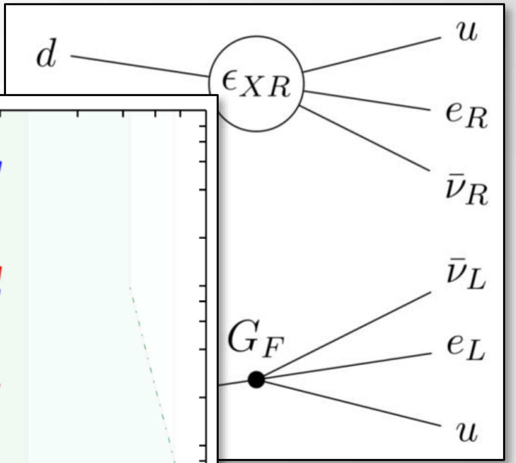




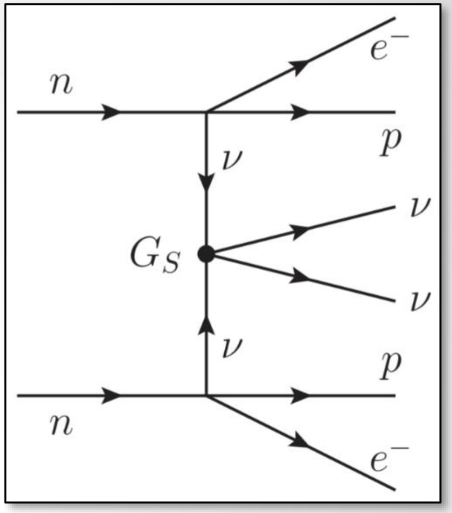
New Physics in $2\nu\beta\beta$

FFD, Graf, Rodejohann, Xu, Phys.Rev.D 102 (2020) 5, 051701

- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

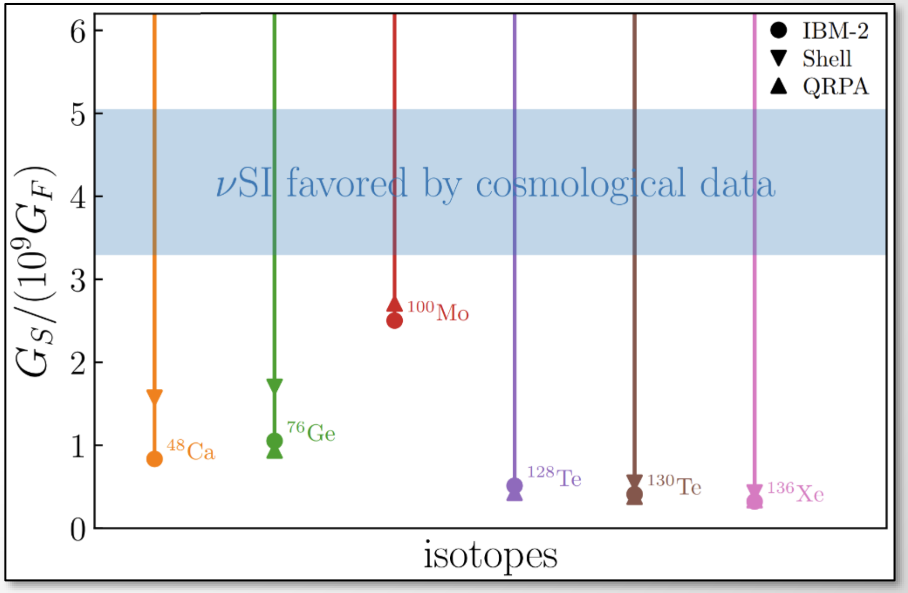
$$\Gamma_{2\nu} + \Gamma_{\nu\mathrm{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}$$

  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Non-observation of enhanced rate



$$\Gamma_{\nu\mathrm{SI}}/\Gamma_{2\nu}^{\mathrm{ex}} < 1$$

excludes regime $G_S \approx 4 \times 10^9\, G_F$ suggested to resolve Hubble tension (Kreisch, Cyr-Racine, Doré, PRD 101 (2020) 12, 123505)



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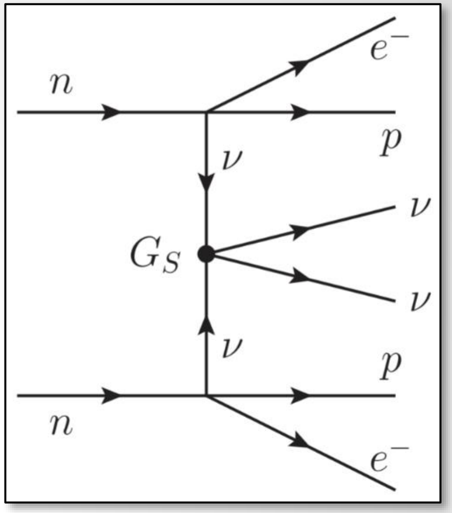
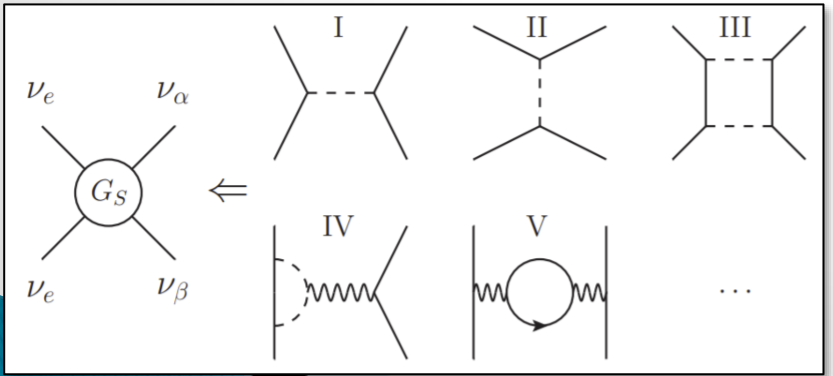
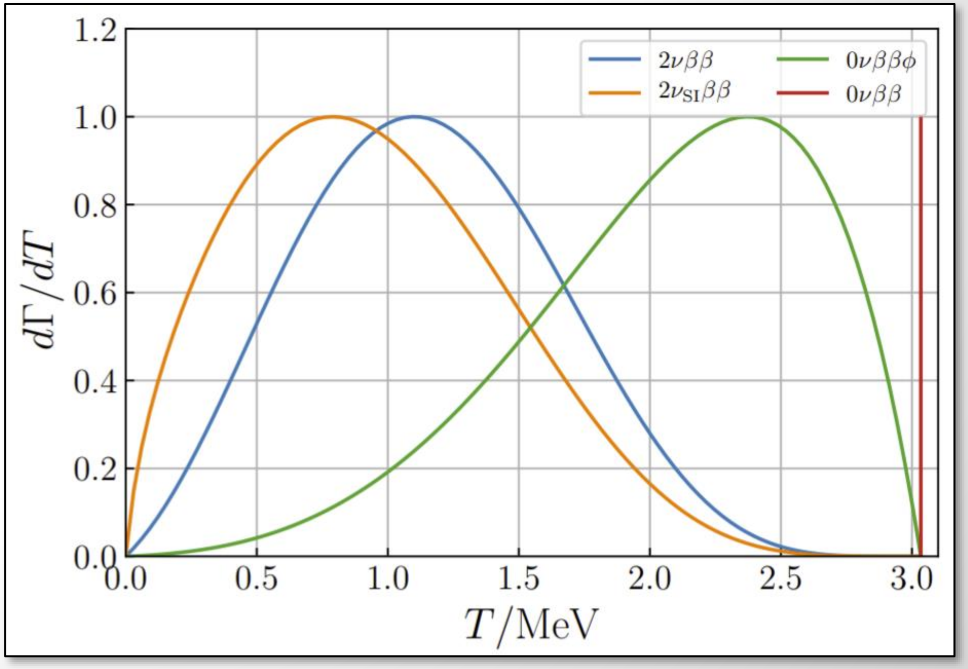
  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Modification of energy spectrum for light mediator(s), e.g., s-channel scalar $m_\phi = Q + 0.1 m_e$







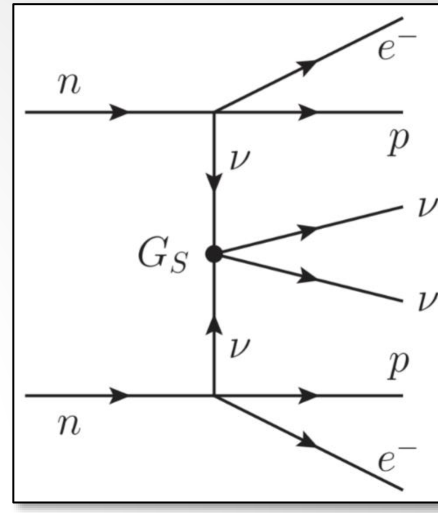
New Physics in $2\nu\beta\beta$

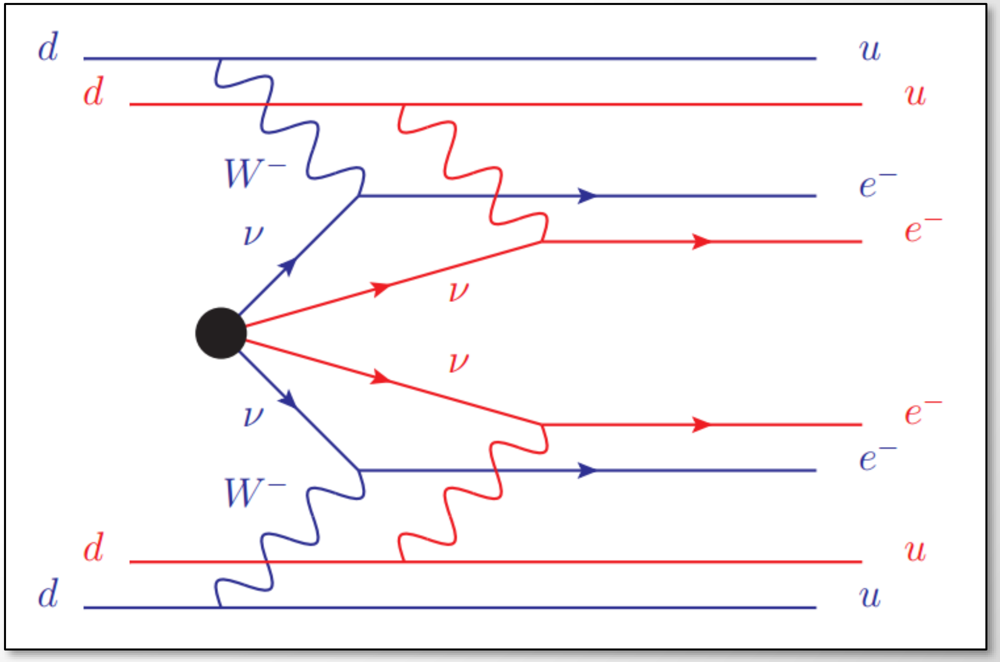
FFD, Graf, Rodejohann, Xu, Phys.Rev.D 102 (2020) 5, 051701

- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

$$\Gamma_{2\nu} + \Gamma_{\nu\mathrm{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}$$

  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Excludes quadruple double β decay



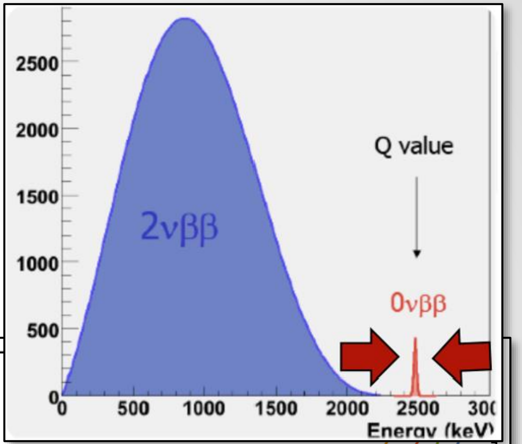


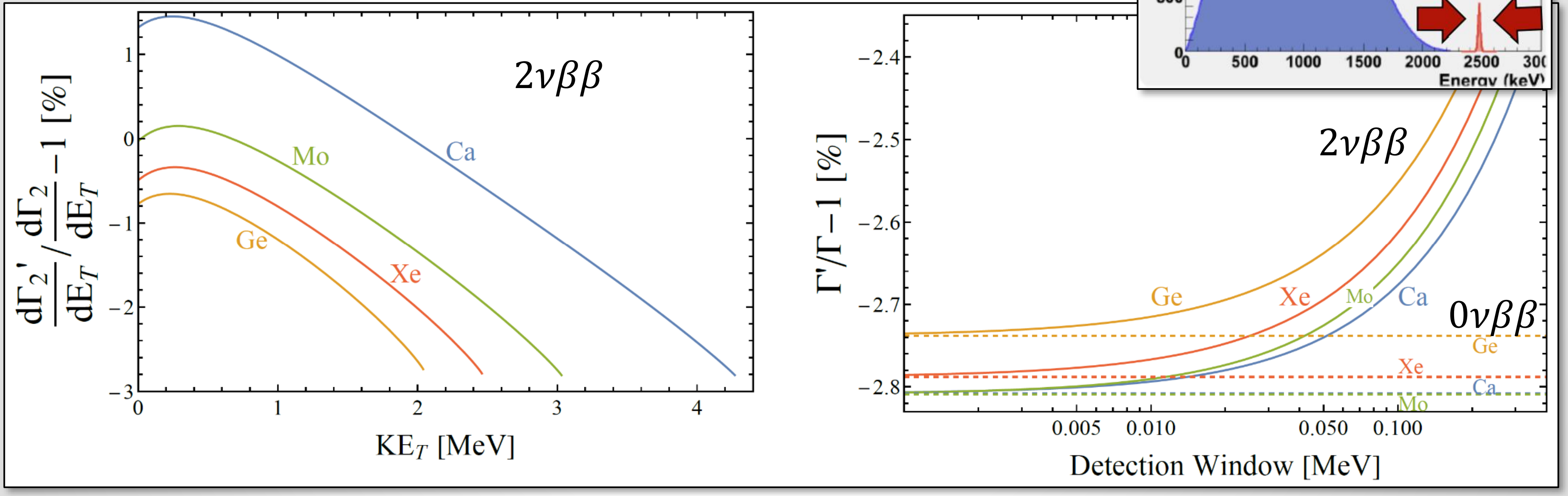
Heeck, Rodejohann
EP Lett. 103 (2013) 32001

SM Corrections to $0/2\nu\beta\beta$

FFD, Canning, Van Goffier, work in progress

- Radiative Corrections
  - Photon-loop and soft photon emission
  - Calculated for β decay (Repko, Wu, PRC 28 (1983) 2433)
  - Application to $0/2\nu\beta\beta$ decay



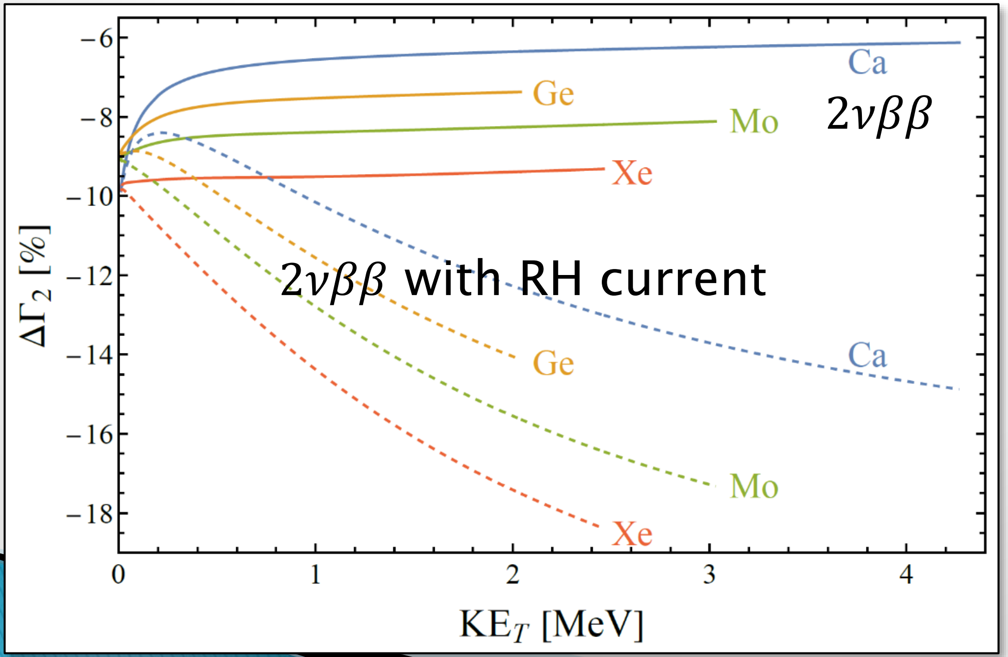


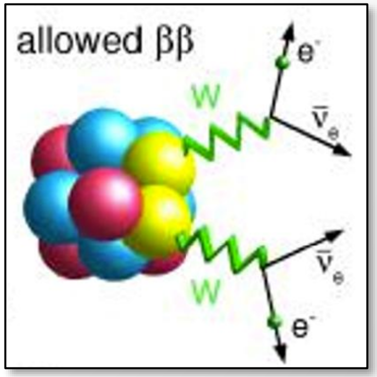
FFD, Canning, Van Goffrier, preliminary

SM Corrections to $0/2\nu\beta\beta$

FFD, Canning, Van Goffier, work in progress

- Radiative Corrections
  - Photon-loop and soft photon emission
  - Calculated for β decay (Repko, Wu, PRC 28 (1983) 2433)
  - Application to $0/2\nu\beta\beta$ decay
- Electromagnetic interaction between emitted electrons
  - Relativistic e^- in Coulomb field of nucleus, atomic e^- **and sister e^-**

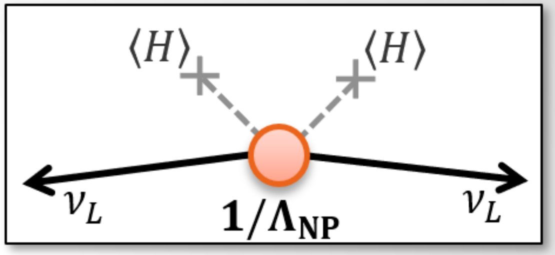




FFD, Canning, Van Goffrier preliminary

Conclusion

- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Universal probe of LNV
  - Proof that light ν are Majorana
  - $m_{\beta\beta} = O(10\ \mathrm{meV})$ ←→ LNV near GUT scale
  - LNV at scales $\Lambda \approx 1\ \mathrm{eV} - 100\ \mathrm{TeV}$



$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\ \mathrm{y}} \approx \left(\frac{\Lambda_{\mathrm{NP}}}{10^{15}\ \mathrm{GeV}}\right)^2$$

- **$2\nu\beta\beta$ is sensitive to New Physics**
  - Conclusion of LNV and Majorana true for $0\nu\beta\beta$ only (no E_{miss})
  - Ongoing and future searches probe $2\nu\beta\beta$ decay with high statistics
  - How well are systematics understood?
    - Experimental and theoretical spectrum
  - Examples considered
    - Majoron emission with RH current
    - Exotic RH currents
    - Sterile neutrino endpoint search
    - Neutrino self-interactions